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Evacuation Simulation of Confined Spaces in Petrochemical Facilities

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Abstract

With the development of petrochemical industry, confined space evacuation has been a major safety issue due to the potential fatalities and injuries caused by inadequate emergency responses. In this work, two existing software, BuildingEXODUS and FDS+Evac, were used to simulate the Required Safe Egress Time (REST) in different evacuation environments. Vertical and horizontal storage tanks were constructed by using these two simulation software. Then, different parameters such as occupant load, with and without internal obstruction, and exit size were studied in different simulation scenarios. The simulation results from the software have shown a good agreement with those from the field experiments. It is found that the REST of vertical storage tank is nearly half of that of horizontal storage tank. The work has demonstrated a concept that the fire safety software could be used to simulate evacuations from confined spaces in petrochemical facilities.

1. Introduction

Confined space evacuation is a major safety concern in the petrochemical and chemical industries [1]. There are a variety of such spaces in the petrochemical and chemical industries, including storage tanks, reaction vessels, distillation columns, pipeline, and boilers. In order to decrease the risk of casualty and property losses during an emergency in confined spaces, it is necessary to know the related Required Safe Egress Time (REST) and other major safety factors in petrochemical plants. However, for confined space evacuations, there are neither field tests nor computer software available. Since some fire safety evacuation simulation tools have been widely used in the design of building evacuations, it is possible to adapt them to petrochemical plant evacuations. For example, Thompson and Marchant have conducted a study on a group of people went through a number of exits with different widths by using SIMULEX [2]. Simulation of Transient Evacuation and Pedestrian Movements (STEPS) was used to calculate the REST under different conditions in a subway transfer station [3]. Furthermore, Yuan et al have modeled the safety evacuation by using BuildingEXODUS, while Yang et al have simulated fire emergency evacuation based on Fire Dynamics Simulator with Evacuation (FDS+Evac) [4, 5]. Hu and Chen took advantage of Pathfinder software in simulating the library evacuation [6]. It is our idea that some simulation tools could help determine the REST and effect of different features for process equipment.

BuildingEXODUS was developed by the fire safety engineering group at the University of Greenwich. The software is based on safety codes to meet the challenging demands of the interaction between people, and interaction between people and structure [7]. Based on five sub models (people, movement, behavior, toxic and hazards), BuildingEXODUS can track the movement as well as the injury of each individual due to heat, toxic gas and fire in specific areas. FDS+Evac was developed by the VTT Technical Research Centre of Finland, which is an agent based fire evacuation model. This software can estimate the total evacuation time, human response and movement in case of hazard conditions by considering human's characteristic behaviors [8]. FDS+Evac considers each occupant as a specific agent that has its own personal properties and escape strategies.

In this work, these two building evacuation software were adapted to make evacuation simulations. Storage tanks were selected as the first example because they are simple process equipment and similar to building structures. Evacuation from three storage tanks including one vertical and two horizontal were simulated. Different parameters such as occupant load, with and without internal obstruction, and exit size were studied in different simulation scenarios. The simulation results are compared with a few experimental results collected from field tests in a Phillips 66 plant. The purpose of this paper is to illustrate the modeling procedure for storage tanks by using BuildingEXODUS and FDS+Evac, and to discuss the feasibility of such software applied in petrochemical industry. Some suggestive advices were provided to optimize the safety factors in storage tanks, which would be beneficial to storage tank operators and onsite engineers.

2. Simulation

2.1 Storage Tank Sizes

Three storage tanks with different openings were used to determine exit times from corresponding confined spaces. These specific vessels were located on the training grounds of the Phillips 66 Borger refinery, TX. Table 1 shows the size of these three storage tanks. The first vessel is a 20-foot tall vertical vessel which has a 12-foot diameter and an opening of 2 feet by 5 feet. The second vessel is a 20-foot long horizontal vessel with a 12-foot diameter and a 20-inch diameter circular opening on one end. The third one is a 20-foot long horizontal vessel with a 12-foot diameter and an 18-inch by 20-inch oval opening on one end. Fig. 1 shows these three storage tanks.

Table 1 Size of three storage tanks

Tanks	**Orientation**	**Size**	**Diameter**	**Opening**
a	Vertical	20-foot tall	12 foot	2×5 feet^2
b	Horizontal	20-foot long	12 foot	20-inch diameter
c	Horizontal	20-foot long	12 foot	18-inch by 20-inch oval

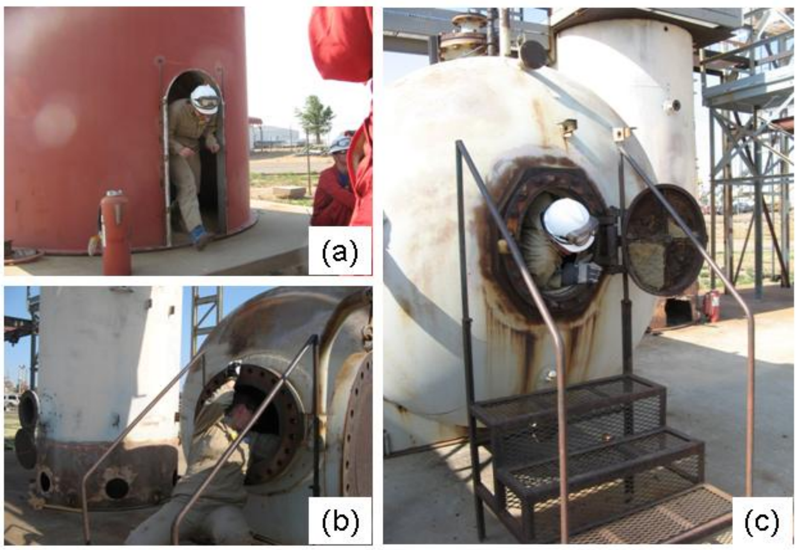

Fig. 1. Three storage tanks with different openings

2.3 Parameter Determinations

Variables, such as the exit size, the length, the occupant load, the movement speeds at emergency, whether people wear the protective clothing and with or without obstruction were set up in the software. Whether people wear the protective clothing was included in the movement speeds.

2.3 Software Settings

The storage tanks are in cylinder, which makes it impossible to draw a cylindrical model in the building-based software. The design of cylindrical storage tanks in petrochemical industry was initially to decrease the gas release possibilities, and they have nothing to do with evacuation. For the evacuation purpose, it is reasonable to simplify these tanks into cuboids. In BuildingEXODUS, nodes are typically separated by 0.5 m [9]. For this model, we used 7×7 nodes for the vertical storage tank, and 12×7 nodes for the horizontal storage tanks. Since the software only deals with 2-dimensional evacuation, we could not model the height effects of the exits. In FDS+Evac simulation, the mesh size is chosen to be 0.01 m. Similarly, the evacuation exit was simplified as rectangle instead of the circle or oval by using their diameters as width and height. Since the minimum node in BuildingEXODUS is 0.5 m, we set the exit width to be 0.5 m for both horizontal storage tanks. Occupant loads inside the storage tanks are set as 1, 3, and 6 [10].

In these 2-dimensional models for horizontal storage tanks, two layers of nodes in BuildingEXODUS and two layers of meshes in FDS+Evac were constructed in order to meet the requirement of the center opened exit on one side of the vessels. In real storage tanks, metal ladders are used for the occupants to climb up to the external exit. However, there are no ladders in the building-based software. Since the staircase could be created in the software and they have the same function as ladders, we replace the ladders by staircases. Fig. 2 and Fig. 3 show the vertical and horizontal simplified models in BuildingEXODUS. The blue dots represent occupants. In Fig.3, the ground plane was connected with the staircase by Link 0. Fig. 4 and Fig. 5 show the vertical and horizontal simplified models in FDS+Evac. The green aperture on the right side wall is the exit. These figures show the occupant load of 6, but in simulation we used 1, 3 and 6.

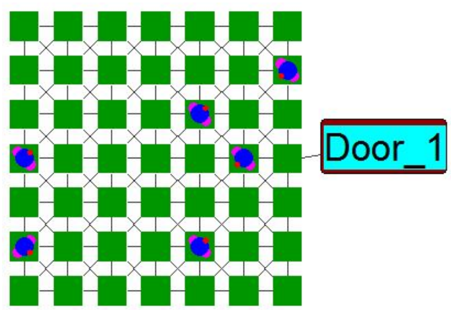

Fig. 2. Vertical storage tank simplified model in BuildingEXODUS

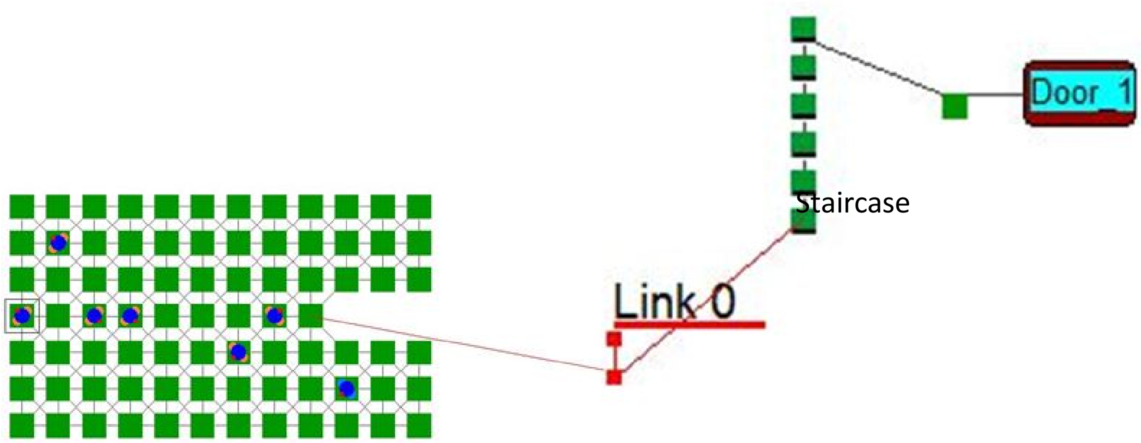

Fig. 3. Horizontal storage tank simplified model in BuildingEXODUS

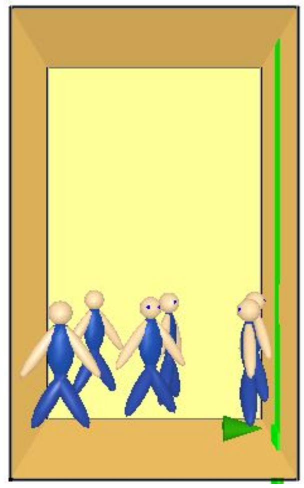

Fig. 4. Vertical storage tank simplified model in FDS+Evac

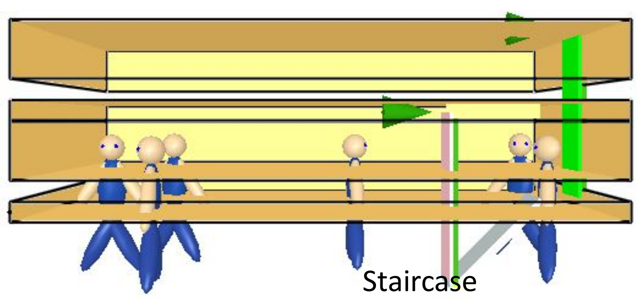

Fig. 5. Horizontal storage tank simplified model in FDS+Evac

The initial positions of occupants are generated randomly by the software. The reaction time of occupant is set to be 0 s. It is assumed that all occupants know the location of exit and the walking speed is 0.8±0.3 m/s. The climbing-up speed is 0.1 m/s. The dimension of the internal obstruction is $1.5\times0.5\times0.5$ m^3. For vertical tanks, the obstruction is placed 1.0 m away from the exit, while for horizontal tanks, it is placed 1.0 m in front of the ladder.

3. Results and Discussions

Five simulations were performed for each scenario. Occupant loads of 1, 3 and 6 were simulated both with and without internal obstruction. Moreover, experimental data were compared with the simulation results for the horizontal storage tank.

3.1 REST without Internal Obstruction

Table 2 REST without internal obstruction

		Vertical Storage Tank		**Horizontal Storage Tank**	
Software	Occupant Load	REST		REST	
		Range	Average	Range	Average
Building Exodus	1	3-6	3.8	18-21	18.9
	3	14-16	15.3	27-33	30.3
	6	27-32	28.7	52-60	55.2
FDS+ Evac	1	4-8	5.7	13-20	17.2
	3	17-20	18.5	20-33	29.8
	6	28-34	30.2	54-62	55.6

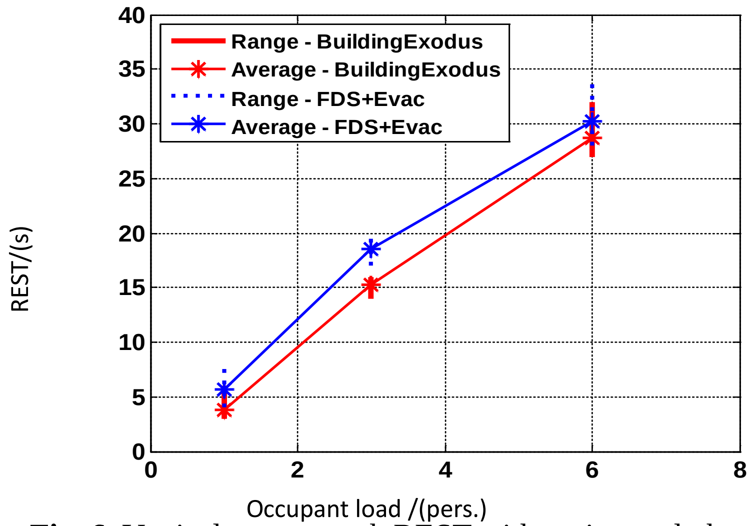

Fig. 6. Vertical storage tank REST without internal obstruction

Table 2 shows the REST of vertical and horizontal storage tanks without internal obstruction when the occupant loads are 1, 3 and 6, respectively. Fig. 6 shows the range and average REST for vertical storage tank without obstruction simulated by BuildingEXODUS and FDS+Evac. The horizontal axis is the occupant load and the vertical axis is the REST in unit of second. In BuildingEXODUS, with the increase of occupant load from 1 to 6, the average REST increases from 3.8 s to 28.7 s nearly linear. According to FDS+Evac simulation results, the average REST increases from 5.7 s to 30.2 s as occupant load increases. The simulation results conducted by using software agree very well with each other. The RESTs from BuildingEXODUS are 2 to 3 seconds shorter than that from FDS+Evac. The reason is randomness of the initial position generated by computer. The general trend of the range and the average REST in BuildingEXODUS and FDS+Evac are close to each other. These results indicate the possibility of adapting such software into storage tank simulation. As for the evacuation time of confined spaces, it is a must to choose the maximum REST as a requirement for the design of such facilities.

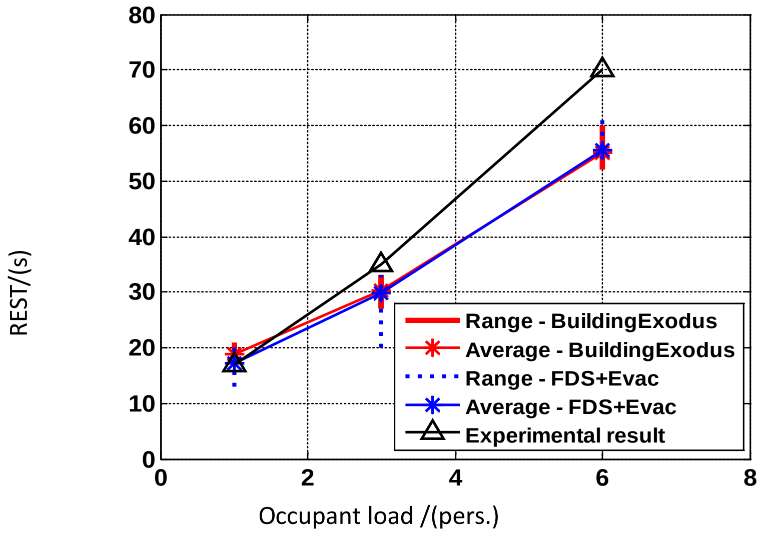

Fig. 7. Horizontal storage tank REST without internal obstruction

Fig. 7 shows the range and average REST for horizontal storage tank without obstruction simulated by BuildingEXODUS and FDS+Evac. The general range and trend of both simulation results agree well with each other. The average RESTs of this model are very close to each other. Moreover, by comparing the horizontal storage tank to the vertical one, it is found that the horizontal RESTs are nearly two times of that in vertical tank. So it is recommended to use vertical tank when two options are available.

For the REST of horizontal storage tank without obstruction, experimental data were collected in the Phillips 66 Borger refinery, TX. Comparing with the experimental results, the simulation results show less evacuation time. The difference of REST between experimental and simulation increases with the increase of occupant load. It takes nearly 2 to 4 s longer for each occupant to evacuate in the experiment. This is quite normal because of the different time measuring mechanism between experiment and simulation. In the experiment, the REST is measured after the evacuees go through the exit and land on the ground. However, in the simulation, software only account for the time when they are going through the exit.

3.2 REST with Internal Obstruction

Table 3. REST with internal obstruction

		Vertical Storage Tank		**Horizontal Storage Tank**	
Software	Occupant Load	REST		REST	
		Range	Average	Range	Average
Building Exodus	1	5-6	5.5	19-21	19.9
	3	25-28	26.2	20-32	28.5
	6	38-39	38.2	54-63	58.4
FDS+ Evac	1	5-7	5.8	15-25	19.2
	3	23-27	26.3	25-39	33.8
	6	41-43	42.3	65-73	69.5

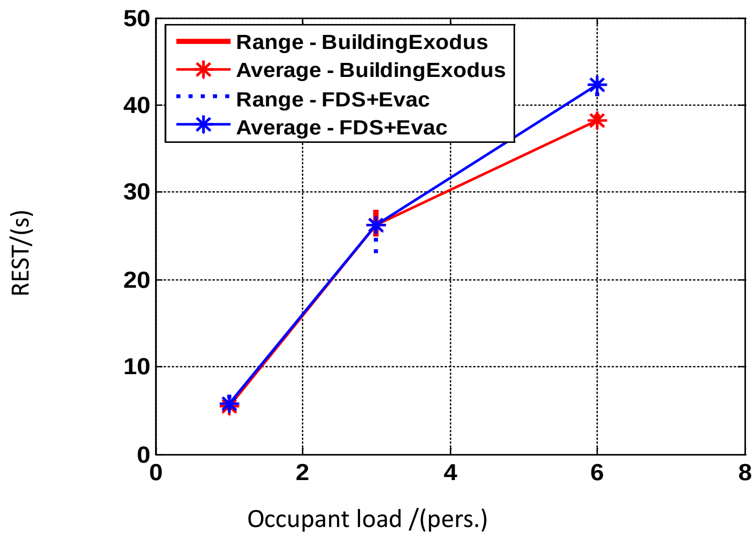

Fig. 8. Vertical storage tank REST with internal obstruction

In this simulation, an internal obstruction is placed in the model. Table 3 shows the RESTs of vertical and horizontal storage tanks with internal obstruction.

Fig. 8 shows the range and average RESTs for vertical storage tank with the obstruction simulated by BuildingEXODUS and FDS+Evac. When there is one evacuee inside, the two software show nearly the same evacuation time. Similar convergence also happens when the evacuee number is 3, they have almost the same average REST (one is 26.2 s and the other one is 26.3 s) and with a little variance in REST range. However, when the number of evacuee increases to 6, the range and average REST deviates by nearly 5 s. This is primarily because of the increase of people interaction in crowd dynamics and the different choices made by people when facing the internal obstruction. Comparing the results of without and with internal obstruction in Figs. 6 and 8, it takes nearly 1.5 to 3 s longer for each occupant to evacuate with internal obstruction inside. As the occupant number increases, the REST difference becomes more and more significant.

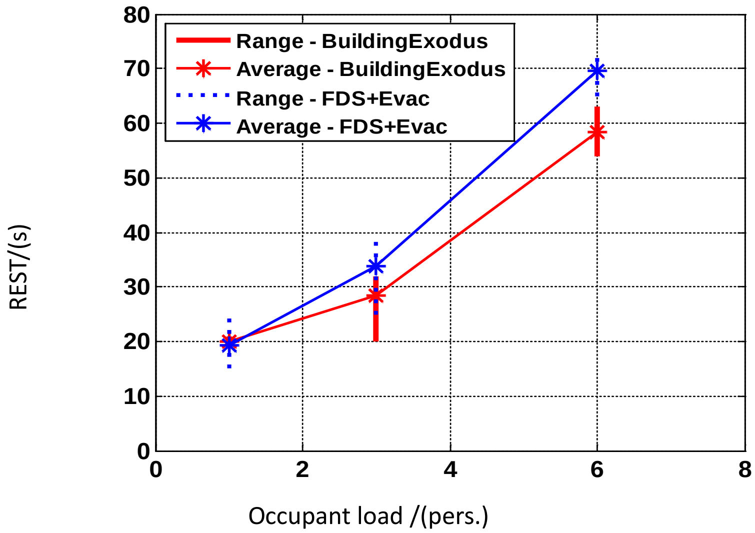

Fig. 9. Horizontal storage tank REST with internal obstruction

Fig. 9 shows the range and average REST for horizontal storage tank with an internal obstruction simulated by BuildingEXODUS and FDS+Evac. When there is 1 occupant, the average RESTs are close to each other. As for the range of RESTs, FDS+Evac covers a larger range than that in BuildingEXODUS. With the number of occupants increase, a more significant difference occurs. The difference is due to the mechanism of human interaction and the calculation method of the software. Generally, the results show good agreement with each other because of the consistency trend and its acceptable variance.

From Figs. 8 and 9, it is concluded that the REST simulated by BuildingEXODUS is longer than that by FDS+Evac. Moreover, REST in vertical tank is nearly half of that in horizontal tank. Comparing the results of without and with internal obstruction in Figs. 7 and 9, it takes longer for people to evacuate from tanks with obstruction than from tanks without obstruction. This is due to the inconvenience between people and the obstruction, which takes more time to decide the right pathways to avoid obstructions.

4. Conclusions

In this paper, we illustrate a method to simulate REST by using BuildingEXODUS and FDS+Evac software, which proves that the fire safety software could be utilized in evacuation simulation in petrochemical facilities. In the simulation, different occupant loads are explored. The influence of internal obstruction is also studied. The results from two software show very good agreement. Furthermore, the simulation results for horizontal tank without internal obstruction are compared with the field test data. The experimental and simulation results are consistent with each other very well. Since BuildingExodus is visualized software, the simulation results are more reliable. FDS+Evac focuses more on the interaction, hence it may not be as good as BuildingExodus in simulating well-trained workers inside confined spaces. Based on simulation results, it is recommended to design and use vertical storage tanks since only half of the evacuation time is needed comparing to horizontal tanks.

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